

# On the Origin of the Tunneling Asymmetry in the Cuprate Superconductors

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## Abstract

We argue the coherent part of the spectral weight always contribute symmetrically to the STM spectrum at sufficiently low energy and the tunneling asymmetry is a manifestation of the incoherent part of the electron spectrum. By subtracting the particle side spectrum from the hole side spectrum in the published STM data of Pan *et al* on  $BSCCO_{2212}(T_c = 84K)$ , we find the difference spectrum show a well defined gap structure at 25 meV. We argue this gap may represent a new energy scale of the system, namely the energy scale for spin-charge recombination in this system.

The scanning tunneling microscopy (STM) plays an important role in the study of the high temperature superconductors since it can provide local information on the single particle properties with ultrahigh energy resolution. A striking feature in the STM spectrum of the high temperature superconductors is their remarkable particle-hole asymmetry. The hole side of the spectrum always dominates the particle side of the spectrum in hole doped cuprates[1].

This asymmetry is not at all surprising if we take the high temperature superconductors as doped Mott insulators described by the  $t - J$  model. In such a doped Mott insulator, an added electron has a reduced probability to contribute to the spectral weight in the low energy subspace of no doubly occupied site. More specifically, if the hole density in the system is  $x$ , then the total spectral weight in the particle side of the spectrum will be reduced to  $x$ , while the total spectral weight in the hole side of the spectrum is not affected by the no double occupancy constraint. Thus the total spectral weight is particle-hole asymmetric for small  $x$ . However, such an asymmetry on the total spectral weight tells us nothing about the distribution of the spectral weight at low energy. To address the problem of tunneling asymmetry near the chemical potential, we need more detailed information on the low energy excitation spectrum of the system.

Rantner and Wen addressed this problem in the slave-Boson mean field theory of the  $t - J$  model[2]. In their theory, the electron spectrum in the superconducting state can be divided into the coherent part and the incoherent part. The particle-hole asymmetry of the tunneling spectrum comes from the incoherent part of the spectral weight which is totally absent in the particle side of spectrum at zero temperature. In the slave-Boson mean field theory, the electron is split into two parts,  $c_{i\sigma} = b_i^\dagger f_{i\sigma}$ , in which  $b$  is the operator for Bosonic holon and  $f$  is the operator for Fermionic spinon. In the mean field theory, the superconductivity is achieved by pairing up the spin one-half spinon and Bose condense the charge one holon. The electron propagator is the convolution of the spinon propagator and the holon propagator. In the presence of the holon condensate, the electron spectrum can be divided into the coherent part and the incoherent part. The coherent part of spectrum originates from the holon condensate and has well defined dispersion (which is nothing but the spinon dispersion). The incoherent part of the spectral weight originates from holon excitation above the condensate and constitutes a continuum in the electron spectrum. In

the mean field theory, the incoherent part of the spectral weight is totally absent in the particle side of the spectrum at zero temperature since all holon are condensed into the lowest energy state while by adding an electron into system we must remove a holon from the system. Thus if we neglect the asymmetry of spinon dispersion near the chemical potential, the tunneling asymmetry can be totally attributed to the incoherent part of spectral weight of electron propagator.

Recently, Anderson and Ong addressed the same problem with a variational approach[3]. They constructed explicitly the variational wave function for the ground state and the excited state of the  $t - J$  model following the original RVB idea. In their treatment, the particle-hole asymmetry is taken into account explicitly in the variational wave function by the introduction of a so called fugacity factor. This fugacity factor plays part of the role of the Gutzwiller projection into the subspace of no double occupancy. In this theory, most of the electron spectral weight is coherent(has well defined dispersion and corresponds to well defined wave function). Unlike Rantner's theory, the tunneling asymmetry is not related to the incoherent part of the spectral weight.

In this paper, we argue the coherent part of the spectral weight of an electronic system always contribute symmetrically to the STM spectrum at sufficiently low energy and the particle-hole asymmetry at low energy is a manifestation of the incoherent part of the electron spectrum. By subtracting the particle side spectrum from the hole side spectrum in published STM data of Pan *et al* (on  $BSCCO_{2212}$  with  $T_c = 84K$ ), we find the tunneling asymmetry appear only above a well defined energy gap of about 25 meV. We argue this gap may represent a new energy scale of the system, namely the energy scale for spin-charge recombination in this system.

By definition, the coherent part of the spectral weight of an electron(or a hole) comes from the contribution of quasiparticle(or quasihole). In the Landau theory of Fermi liquid, the quasiparticle(quasihole) plays a dual role. On the one hand, the quasiparticle(quasihole) can be thought of as a particle-like(hole-like) elementary excitation on the ground state of a  $N$  particle system. On the other hand, the quasiparticle(quasihole) can also be thought of as a constituent of the grounds state of the  $N + 1$  particle( $N - 1$  particle) system, provide that the quasiparticle(quasihole) is on the Fermi surface. The coherent part of the spectral weight for adding an electron into the system on the Fermi surface is thus equal to the

square of the matrix element of the electron creation operator between the ground state of  $N$  particle system and the ground state of  $N + 1$  particle system,

$$Z_N^a = |\langle g_{N+1} | c_k^\dagger | g_N \rangle|^2$$

while the coherent part of the spectral weight for removing an electron from the system on the Fermi surface is equal to the square of the matrix element of electron annihilation operator between the ground state of  $N$  particle system and the ground state of  $N - 1$  particle system,

$$Z_N^r = |\langle g_{N-1} | c_k | g_N \rangle|^2 = Z_{N-1}^a$$

In the thermodynamic limit, we have

$$Z_N^r = Z_{N-1}^a \simeq Z_N^a$$

thus the coherent part of the spectral weight is particle-hole symmetric. This conclusion is consistent with that of the slave-Boson mean field theory. In the presence of the superconducting pairing, the above argument is not applicable. However, since the no double occupancy constraint (which is believed to be the ultimate reason for particle-hole asymmetry in this system) occurs at an energy scale much higher than that of the superconducting pairing, we do not expect the latter to change our conclusion essentially.

Since the coherent part of the spectral weight is particle-hole symmetric, the tunneling asymmetry must be attributed to the incoherent part of the electron spectrum. Thus from the STM spectrum we can extract information on the incoherent part of the electron spectrum. For a strongly correlated system like cuprates, such information is of great importance. From such information we can in principle figure out the mechanism by which a bare particle decay into the many particle excitations and thus on the nature of the many particle excitations itself. In the context of the cuprates, two mechanisms of generating electron incoherence are frequently discussed. The first is by scattering with some bosonic collective mode in the system. Among such collective modes, the neutron resonance mode in the spin channel[4, 5] and the oxygen stretching phonon mode are most frequently involved[6]. Such a mechanism can provide a natural energy scale for the incoherent part of the spectral weight if the collective mode itself is gapped. The second mechanism to generate electron

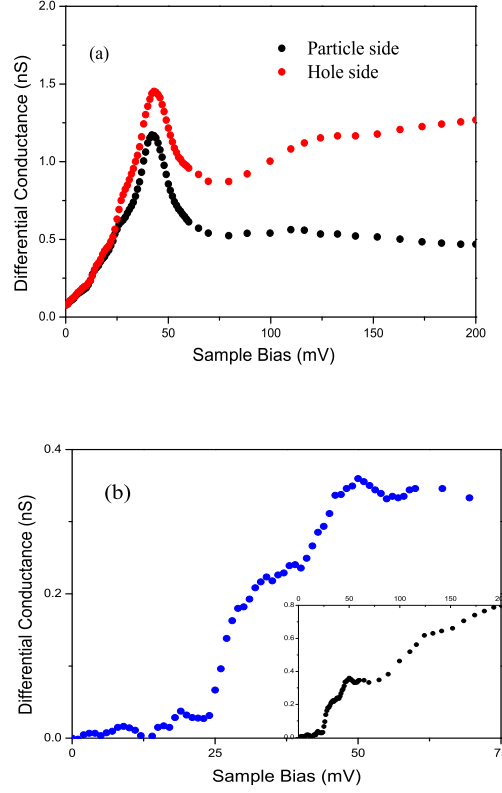


FIG. 1: The STM spectrum of  $BSCCO_{2212}$  ( $T_c = 84K$ ). (a) Original data of Pan *et al* [1](data points above 60 mV are only partly reproduced in this figure for clearness). (b) The difference spectrum obtained by subtracting the particle side spectrum from the hole side spectrum. The inset show the difference spectrum in the whole range of energy measured by Pan *et al*.

incoherence is by spin-charge separation as we have discussed in the slave-Boson mean field theory[2]. In this mechanism, the electron split into two elementary excitations carrying its spin and charge quantum number separately. The independent propagation of the two elementary excitations lead to electron incoherence. We note such a mechanism do not provide a natural energy scale for the incoherent part of the spectral weight.

Along this line of reasoning, we have extracted the asymmetric part of the STM spectrum by subtracting the particle side spectrum from the hole side spectrum in the published STM data of Pan *et al* on  $BSCCO_{2212}$ [1]. The result is shown in Figure 1 and is rather striking. We find the tunneling asymmetry occurs only above a well defined gap about 25 meV. This indicate that the incoherent part of the electron spectral weight has a well defined energy scale. This is the main result of this paper.

Now we discuss the possible origin of the energy gap in the difference spectrum. In the collective mode scattering scenario, the incoherent part of the spectral weight do show a energy scale if the collective mode itself is gapped. However, the extracted gap for the incoherent part of the spectral weight, namely, 25meV, seems too small for such a explanation to apply. In the system studied, the energy of the neutron resonance mode  $E_r$  can be estimated from the  $T_c - E_r$  scaling to be  $E_r \sim 37$  meV. Thus we expect the incoherent part of the spectral weight to begin above 37 meV. The phonon mechanism involve an energy scale even higher than that of the neutron mode (70 meV) and is thus also too high to explain the gap in the difference spectrum. At the same time, this mechanism provide no simple understanding of the dominance of the hole side spectrum over the particle side spectrum. For these reasons, the collective mode scattering is not likely the main origin of the electron incoherence and thus the tunneling asymmetry of the cuprates. However, we think the scattering with the neutron resonance mode may be responsible for the broad peak centered at 50 meV in the difference spectrum.

Now we analyse the tunneling asymmetry in the spin-charge separation scenario. In this scenario, the dominance of the hole side spectrum is directly related to the no double occupancy constraint, as we have discussed in the slave-Boson mean field theory of the  $t - J$  model. One problem with this scenario is that the spin-charge separation itself do not provide a natural energy scale for the incoherent part of the spectral weight. In the slave Boson mean filed theory, the incoherent part of the spectral weight start at zero energy since the density of state for a holon dispersion is a constant at low energy in the two dimensional system. Here we propose that the energy gap in the difference spectrum may represent a new energy scale in the system, namely, the energy scale for spin-charge recombination. Below this energy scale, the spectral weight is totally coherent and the electron propagate as an integrated part in the system. Above this energy scale, an electron dissociated into two parts carrying its spin and charge quantum number separately. The two parts propagate independently and make up the incoherent part of the electron spectrum. The detail of the spin-charge recombination process is still unknown and we call for further theoretical study on this problem.

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